

Right-handed Neutrinos in $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ Elastic Scattering

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In this paper a scenario admitting the participation of the exotic right-handed scalar g_S^R coupling in addition to the standard left-handed g_V^L, g_A^L couplings in the low-energy $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ scattering is considered. The main goal is to show how the presence of the right-handed neutrinos in the $(\nu_\mu e^-)$ scattering changes the laboratory differential cross section in relation to the Standard Model prediction. The $(\nu_\mu e^-)$ scattering is studied at the level of the four-fermion point interaction. Muon-neutrinos are assumed to be polarized Dirac fermions and to be massive. In the laboratory differential cross section the new interference term between the standard g_V^L coupling of the left-handed neutrino and exotic g_S^R coupling of the right-handed neutrino appears which does not vanish in the limit of massless neutrino. This additional contribution, including information about the transverse components of neutrino polarization, generates the azimuthal asymmetry in the angular distribution of the recoil electrons. This regularity would be the proof of the participation of the right-handed neutrinos in the $(\nu_\mu e^-)$ scattering.

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The $(V - A)$ structure of weak interactions at low energies describes only what has been measured so far. We mean here the measurement of the electron helicity [1], the indirect measurement of the neutrino helicity [2], the asymmetry in the distribution of the electrons from β -decay [3] and the experiment with muon decay [4] which confirmed parity violation [5]. Feynman, Gell-Mann and independently Sudarshan, Marshak [6] established that only left-handed vector V , axial A couplings can take part in weak interactions because this yields the maximum symmetry breaking under space inversion, under charge conjugation; the two-component neutrino theory of negative helicity; the conservation of the combined symmetry CP and of the lepton number. In consequence it led to the conclusion that produced neutrinos in $V - A$ interaction can only be left-handed. However Wu [7] indicated that both standard left-handed $(V, A)_L$ couplings and exotic right-handed $(S, T, P)_R$ couplings may be responsible for the negative electron helicity observed in β -decay. It would mean that generated neutrinos in (S, T, P) interactions may also be *right-handed*. Recent tests do not provide a unique answer as to the presence of the exotic weak interactions. So Shimizu *et al.* [8] determined the ratio of the strengths of scalar and tensor couplings to the standard vector coupling in $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ decay at rest assuming the only left-handed neutrinos for all interactions. Their results indicated the compatibility with the Standard Model (SM) [9, 10, 11] prediction. Bodek *et al.* at the PSI [12] looked for the evidence of the violation of time reversal invariance measuring T -odd transverse components of the positron polarization in μ^+ -decay. They also admitted the presence of the only left-handed neutrinos produced by the scalar interaction. The recent results

presented by the DELPHI Collaboration [13] concerning the measurement of the Michel parameters and the neutrino helicity in τ lepton decays indicated the consistency with the standard $V - A$ structure of the charged current weak interaction. However on the other hand, the achieved precision of measurements still admits the deviation from the pure $V - A$ interaction, i.e. the possible participation of the exotic interactions with the right-handed neutrinos beyond the SM. It is necessary to carry out the new high-precision tests of the Lorentz structure and of the handedness structure of the weak interactions at low energies in which the *components of the neutrino polarization* would be measured, because in the conventional observables the interference contributions coming from the right-handed neutrinos vanish in the limit of massless neutrino [14, 15, 16]. Frauenfelder *et al.* [17] pointed out that one has to measure either the neutrino polarization (spin) or the neutrino-electron correlations to determine the full Lorentz structure of the weak interactions.

The main our goal is to show how the presence of the right-handed neutrinos in the $(\nu_\mu e^-)$ scattering changes laboratory differential cross section in relation to the SM prediction with the left-handed neutrinos. We will consider the process of the $(\nu_\mu e^-)$ scattering at the level of the four-fermion point (contact) interaction. Muon-neutrinos are assumed to be massive Dirac fermions and to be polarized. In these considerations, the incoming neutrinos come from the muon-capture, where the production plane is spanned by the initial muon polarization and the outgoing neutrino momentum. However in practice, the suitable low-energy polarized neutrino source could be the strong chromium source (^{51}Cr). Because there exist the models of the spontaneous symmetry breaking under time reversal [18] in which the scalar weak interaction can appear, the possible participation of the exotic right-handed scalar S coupling in addition to the standard left-handed vector V and axial A couplings

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is admitted. It means that in the $V - A$ interaction, the incoming muon-neutrinos are always left-handed, but in the scalar S interaction the initial neutrinos are right-handed (the outgoing neutrinos are left-handed). The couplings constants are denoted as g_V^L, g_A^L and g_S^R respectively to the incoming neutrino handedness:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \{ (\bar{u}_{e'} \gamma^\alpha (g_V^L - g_A^L \gamma_5) u_e) (\bar{u}_{\nu_{\mu'}} \gamma_\alpha (1 - \gamma_5) u_{\nu_\mu}) + \frac{1}{2} g_S^R (\bar{u}_{e'} u_e) (\bar{u}_{\nu_{\mu'}} (1 + \gamma_5) u_{\nu_\mu}) \}, \quad (1)$$

where u_e and $u_{e'}$ (u_{ν_μ} and $u_{\nu_{\mu'}}$) are the Dirac bispinors of the initial and final electron (neutrino) respectively, $G_F = 1.16639(1) \times 10^{-5} \text{GeV}^{-2}$ is the Fermi coupling

constant [19]. In our considerations the system of natural units with $\hbar = c = 1$, Dirac-Pauli representation of the γ -matrices and the $(+, -, -, -)$ metric are used [20].

Because the carried out investigations for the μ^- -capture [16] led to the conclusion that the production of the right-handed neutrinos by the exotic scalar interaction manifests the non-vanishing transverse components of the neutrino polarization in the limit of massless neutrino, one expects the similar regularity in the $(\nu_\mu e^-)$ scattering. The matrix element for the μ^- -capture and formula on the magnitude of the transverse neutrino polarization vector $|\eta_\nu^T|$, in the limit of vanishing neutrino mass, were as follows:

$$\mathcal{H}_{\mu^-} = C_V^L (\bar{\Psi}_\nu \gamma_\lambda (1 - \gamma_5) \Psi_\mu) (\bar{\Psi}_n \gamma^\lambda \Psi_p) + C_A^L (\bar{\Psi}_\nu i \gamma_5 \gamma_\lambda (1 - \gamma_5) \Psi_\mu) (\bar{\Psi}_n i \gamma^5 \gamma^\lambda \Psi_p) + C_S^R (\bar{\Psi}_\nu (1 - \gamma_5) \Psi_\mu) (\bar{\Psi}_n \Psi_p), \quad (2)$$

$$|\eta_\nu^T| = \frac{\sqrt{\langle \mathbf{S}_\nu \cdot (\hat{\mathbf{P}}_\mu \times \hat{\mathbf{q}}) \rangle_f^2 + \langle \mathbf{S}_\nu \cdot \hat{\mathbf{P}}_\mu \rangle_f^2}}{\langle 1 \rangle_f} = |\mathbf{P}_\mu| \left| \frac{C_S^R}{C_V^L} \right| \left(1 + \frac{q}{2M} \right) \quad (3)$$

$$\times \left\{ \left(3 + \frac{q}{M} \right) \left| \frac{C_A^L}{C_V^L} \right|^2 + \left(1 + \frac{q}{M} \right) + \left| \frac{C_S^R}{C_V^L} \right|^2 - \frac{q}{M} \left| \frac{C_A^L}{C_V^L} \right| \cos(\alpha_{AV}^L) \right\}^{-1},$$

$$\langle \mathbf{S}_\nu \cdot (\hat{\mathbf{P}}_\mu \times \hat{\mathbf{q}}) \rangle_f = -\frac{|\phi_\mu(0)|^2}{4\pi} |\mathbf{P}_\mu| \left(1 + \frac{q}{2M} \right) \text{Im}(C_V^L C_S^{R*}), \quad (4)$$

$$\langle \mathbf{S}_\nu \cdot \hat{\mathbf{P}}_\mu \rangle_f = \frac{|\phi_\mu(0)|^2}{4\pi} |\mathbf{P}_\mu| \left(1 + \frac{q}{2M} \right) \text{Re}(C_V^L C_S^{R*}), \quad (5)$$

where C_V^L, C_A^L, C_S^R - the complex coupling constants for the standard vector, axial and exotic scalar weak interactions denoted respectively to the outgoing neutrino handedness; $\langle \mathbf{S}_\nu \cdot (\hat{\mathbf{P}}_\mu \times \hat{\mathbf{q}}) \rangle_f, \langle \mathbf{S}_\nu \cdot \hat{\mathbf{P}}_\mu \rangle_f, \langle 1 \rangle_f$ - the T -odd and T -even transverse components of neutrino polarization and the probability of muon capture, respectively; q, M - the value of the neutrino momentum and the nucleon mass; $|\mathbf{P}_\mu|$ - the value of the muon polarization in $1s$ state; $\phi_\mu(0)$ - the value of the large radial component of the muon Dirac bispinor for $r = 0$; $\hat{\mathbf{q}}, \hat{\mathbf{P}}_\mu$ - the direction of the neutrino momentum and of the muon polarization, respectively; $\alpha_{AV}^L \equiv \alpha_A^L - \alpha_V^L$ - the relative phase between the standard C_A^L and C_V^L couplings.

It can be seen that the neutrino observables consist exclusively of the interference term between the standard left-handed vector V_L coupling and exotic right-handed scalar S_R coupling. It can be understood as the interference between the neutrino waves of negative and positive handedness. If we admit also the presence of the left-handed scalar S_L coupling in addition to the right-handed exotic scalar S_R coupling, we get the interferences between the $(V, A)_L$ and S_L couplings proportional to the neutrino mass, and they vanish in the limit of

massless neutrino. Our coupling constants $C_{V,A}^L, C_S^R$ can be expressed by Fetscher's couplings $g_{e\mu}^\gamma$ for the normal and inverse muon decay [19], assuming the universality of weak interactions. The induced couplings generated by the dressing of hadrons are neglected as their presence does not change qualitatively the conclusions about transverse neutrino polarization. Here, $\gamma = S, V, T$ indicates a scalar, vector, tensor interaction; $\epsilon, \mu = L, R$ indicate the chirality of the electron or muon and the neutrino chiralities are uniquely determined for given γ, ϵ, μ . We get the following relations:

$$\begin{aligned} C_V^L &= A(g_{LL}^V + g_{RL}^V), \\ -C_A^L &= A(g_{LL}^V - g_{RL}^V), \\ C_S^R &= A(g_{LR}^S + g_{RL}^S), \end{aligned} \quad (6)$$

where $A \equiv (4G_F/\sqrt{2})\cos\theta_c$, θ_c is the Cabbibo angle. In this way, the lower limits on the $C_{V,A}^L$ and upper limit on the C_S^R can be calculated, using the current data [19]; $|C_V^L| > 0.850A$, $|C_A^L| > 1.070A$, $|C_S^R| < 0.974A$. In consequence, one gives the upper bound on the magnitude of the transverse neutrino polarization vector proportional to the value of the muon polarization; $|\eta_\nu^T| \leq 0.334|\mathbf{P}_\mu|$ (for $\alpha_{AV}^L = 0$). The obtained limit has to be divided by

the $|\mathbf{P}_\mu|$ to have the upper bound on the physical value of the transverse neutrino polarization vector generated by the exotic scalar interaction; $|\boldsymbol{\eta}'^T_\nu|/|\mathbf{P}_\mu| \leq 0.334$.

To describe $(\nu_\mu e^-)$ scattering the following observables are used: $\boldsymbol{\eta}_\nu$ - the full vector of the initial neutrino po-

larization in the rest frame, \mathbf{q} - the incoming neutrino momentum, $\mathbf{p}_{e'}$ - the outgoing electron momentum. The laboratory differential cross section for the $\nu_\mu e^-$ scattering, in the limit of vanishing neutrino mass, is of the form:

$$\frac{d^2\sigma}{dyd\phi_{e'}} = \left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(V,A)} + \left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(S)} + \left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(VS)}, \quad (7)$$

$$\left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(V,A)} = B\{(1 - \boldsymbol{\eta}_\nu \cdot \hat{\mathbf{q}})[(g_V^L + g_A^L)^2 + (g_V^L - g_A^L)^2(1 - y)^2 - \frac{m_e y}{E_\nu}((g_V^L)^2 - (g_A^L)^2)]\}, \quad (8)$$

$$\left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(S)} = B\left\{\frac{1}{8}y\left(y + 2\frac{m_e}{E_\nu}\right)[|g_S^R|^2(1 + \boldsymbol{\eta}_\nu \cdot \hat{\mathbf{q}})]\right\}, \quad (9)$$

$$\begin{aligned} \left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(VS)} = B\bigg\{ & \sqrt{y\left(y + 2\frac{m_e}{E_\nu}\right)}[-\boldsymbol{\eta}_\nu \cdot (\hat{\mathbf{p}}_{e'} \times \hat{\mathbf{q}})Im(g_V^L g_S^{R*}) + (\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{p}}_{e'})Re(g_V^L g_S^{R*})] \\ & - y\left(1 + \frac{m_e}{E_\nu}\right)(\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{q}})Re(g_V^L g_S^{R*})\bigg\}, \end{aligned} \quad (10)$$

$$B \equiv \frac{E_\nu m_e G_F^2}{(2\pi)^2 2}, \quad (11)$$

$$y \equiv \frac{E_{e'}^R}{E_\nu} = \frac{m_e}{E_\nu} \frac{2\cos^2\theta}{(1 + \frac{m_e}{E_\nu})^2 - \cos^2\theta}, \quad (12)$$

where y - the ratio of the kinetic energy of the recoil electron $E_{e'}^R$ to the incoming neutrino energy E_ν , θ - the angle between the direction of the outgoing electron momentum $\hat{\mathbf{p}}_{e'}$ and the direction of the incoming neutrino momentum $\hat{\mathbf{q}}$ (recoil electron scattering angle), m_e - the electron mass, $\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{q}}$ - the longitudinal polarization of the incoming neutrino, $\phi_{e'}$ - the angle between the production plane and the reaction plane.

It can be noticed that the main non-standard contributions to the laboratory differential cross section come from the interference between the standard left-handed vector g_V^L coupling and exotic right-handed scalar g_S^R coupling, whose occurrence does not depend explicitly on the neutrino mass. This interference may be understood as the interference between the neutrino waves of the same handedness for the the final neutrinos. The similar regularity as for μ^- -capture appeared here [16]. The correlation $\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{p}}_{e'}$ proportional to $Re(g_V^L g_S^{R*})$ lies in the reaction plane spanned by the $\hat{\mathbf{p}}_{e'}$ and $\hat{\mathbf{q}}$, and it includes both T -even longitudinal and transverse components of the initial neutrino polarization:

$$(\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{p}}_{e'}) = \cos\theta(\boldsymbol{\eta}_\nu \cdot \hat{\mathbf{q}}) + (\boldsymbol{\eta}'^T_\nu \cdot \mathbf{p}_{e'}^T), \quad (13)$$

where index "T" describes transverse components of the outgoing electron momentum and of the incoming neutrino polarization, respectively. The other correlation $\boldsymbol{\eta}_\nu \cdot (\hat{\mathbf{p}}_{e'} \times \hat{\mathbf{q}})$ proportional to $Im(g_V^L g_S^{R*})$ lies along the direction perpendicular to the reaction plane and it includes only T -odd transverse component of the initial

neutrino polarization:

$$\boldsymbol{\eta}_\nu \cdot (\hat{\mathbf{p}}_{e'} \times \hat{\mathbf{q}}) = \boldsymbol{\eta}'^T_\nu \cdot (\hat{\mathbf{p}}_{e'} \times \hat{\mathbf{q}}). \quad (14)$$

It can be shown that in the full interference term, Eq. (10), the contributions from the longitudinal components of the neutrino polarization annihilate, and in consequence one gives the interference including only the transverse components of the initial neutrino polarization, both T -even and T -odd:

$$\begin{aligned} \left(\frac{d^2\sigma}{dyd\phi_{e'}}\right)_{(VS)} = B\bigg\{ & \sqrt{\frac{m_e}{E_\nu}y[2 - (2 + \frac{m_e}{E_\nu})y]} \\ & \times |g_V^L| |g_S^R| |\boldsymbol{\eta}'^T_\nu \cdot \cos(\phi - \alpha)|\bigg\}, \end{aligned} \quad (15)$$

where $\alpha \equiv \alpha_V^L - \alpha_S^R$ - the relative phase between the g_V^L and g_S^R couplings, ϕ - the angle between the reaction plane and the transverse neutrino polarization vector and it is connected with the $\phi_{e'}$ in the following way; $\phi = \phi_0 - \phi_{e'}$, where ϕ_0 - the angle between the production plane and the transverse neutrino polarization vector. It can be noticed that the contribution from the interference between the g_V^L and g_S^R couplings, involving the transverse neutrino polarization components, will be substantial at lower neutrino energies $E_\nu \leq m_e$ but negligibly small at large energies and vanishes for $\theta = 0$ or $\theta = \pi/2$. The occurrence of the interference term in the cross section depends on the relative phase between the angle ϕ and phase α and does not vanish for $\phi - \alpha \neq \pi/2$. The situation is illustrated in the Fig.1, when $m_e/E_\nu = 1$, $y \in [0, 0.66]$, $\phi - \alpha = 0$ (ESI1(y) - dashed line) and $\phi - \alpha = \pi$ (ESI2(y) - dashed line), respectively. We use the present model-independent upper limits on the non-standard coupling constants [19] obtained from the normal and inverse muon-decay, assuming the universality of weak interaction. We take the

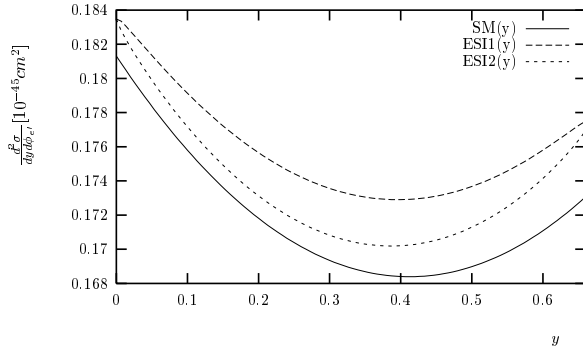


FIG. 1: Plot of the $\frac{d^2 \sigma}{dy d \phi_{e'}}$ as a function y for; a) SM with the left-handed neutrino (SM(y) - solid line), b) the case of the exotic scalar interaction with the right-handed neutrino for $\phi - \alpha = 0$ (ESI1(y)- dashed line) and for $\phi - \alpha = \pi$ (ESI2(y) - dashed line), respectively.

upper bound on the $|\eta_\nu'^T| \leq 0.334$ for the neutrinos coming from the muon-capture (however the phase α is still unknown). The value $|\eta_\nu'^T| = 0.334$ is used to get the upper limit on the expected effect from the right-handed neutrinos in the cross section for the $(\nu_\mu e^-)$ scattering. It means that the value of the longitudinal neutrino po-

larization is equal to $\eta_\nu^L \equiv \eta_\nu \cdot \hat{\mathbf{q}} = -0.943$. The plot for the SM is made with the use of the present experimental values for $g_V^L = -0.041 \pm 0.015$, $g_A^L = -0.507 \pm 0.014$ [19], $\eta_\nu \cdot \hat{\mathbf{q}} = -1$ and $m_e/E_\nu = 1$, Fig.1 (SM(y) - solid line).

It is known that in the SM the angular distribution of the recoil electrons does not depend on the $\phi_{e'}$. It is necessary to analyse all the possible reaction planes corresponding to the given recoil electron scattering angle, e.g. $\theta = \pi/3$, $\theta = \pi/4$, $\theta = 2\pi/9$ (for $E_\nu \leq m_e$) to verify if the azimuthal asymmetry in the cross section appears. The regularity of this type would indicate the possible participation of the right-handed neutrinos in the $(\nu_\mu e^-)$ scattering.

The low-energy high-precision neutrino-electron scattering experiments using the beta-radioactive intense and polarized neutrino source could be used to search for new effects coming from the *right-handed neutrinos*, e. g. the Borexino neutrino experiment with the chromium source [21] (to be published).

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